Integrated Focal Plane Arrays for Millimeter-wave Astronomy

James J. Bock[a], Alexey Goldin[a], Cynthia Hunt[b], Andrew E. Lange[b], Henry G. LeDuc[a], Peter K. Day[a], Anastasios Vayonakis[b], and Jonas Zmuidzinas[b]

[a]*Jet Propulsion Laboratory, Pasadena CA, 91109*
[b]*California Institute of Technology, Pasadena CA, 91125*

Abstract. We are developing focal plane arrays of bolometric detectors for sub-millimeter and millimeter-wave astrophysics. We propose a flexible array architecture using arrays of slot antennae coupled via low-loss superconducting Nb transmission line to microstrip filters and antenna-coupled bolometers. By combining imaging and filtering functions with transmission line, we are able to realize unique structures such as a multi-band polarimeter and a planar, dispersive spectrometer. Micro-strip bolometers have significantly smaller active volume than standard detectors with extended absorbers, and can realize higher sensitivity and speed of response. The integrated array has natural immunity to stray radiation or spectral leaks, and minimizes the suspended mass operating at 0.1 – 0.3 K. We also discuss future space-borne spectroscopy and polarimetry applications.

INTRODUCTION

The sensitivity of current bolometers allows for background-limited performance for photometry at millimeter- to far-infrared wavelengths. At millimeter-wavelengths, the brightness of the cosmic microwave background dominates the sky brightness and sets a photon noise level at the detector of $\sim 1 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$. Since the required detector NEPs are now achieved at $T \leq 0.3$ K [1], further advances in the sensitivity of millimeter-wave focal planes must come from increases in the array format. At millimeter-wavelengths, large format bolometer arrays not only require multiplexing at the sub-K stage, but a significant advance in focal plane architecture.

In practical applications, millimeter-wave bolometers require beam-collimating optics to control their illumination on warm optics. Cryogenic re-imaging optical systems can be used to define the illumination pattern of infrared detectors. However, in the millimeter it is difficult to cool the necessarily large optics below 1-2 K. Since the brightness of the cold optics are similar to the 2.75 K sky brightness, only a modest fraction of the detector throughput can be allowed to couple to black 2 K surfaces. Thus at millimeter wavelengths, bare absorbing pixels cannot be used in low background applications without filtering and collimating optics at $T < 1$ K. While feedhorns provide collimation in current instruments, they can only used with modest numbers of pixels as feedhorns create a significant mass penalty at 0.1 – 0.3 K, preventing practical implementation of the large-format focal plane arrays.

CP605, *Low Temperature Detectors,* edited by F. S. Porter et al.

The next generation of space-borne far-infrared and millimeter-wave experiments will use arrays of feedhorn-coupled bolometers. The Planck High Frequency Instrument (HFI) will operate an array of 48 detectors placed in integrating cavities behind corregated feedhorns at 100 mK. Similarly, the Herschel Space Observatory Spectral and Photometric Imaging Receiver (SPIRE) will have 5 arrays of sub-millimeter bolometers operating at 300 mK for imaging and spectroscopy. In the case of Planck, the HFI focal plane fills much of the available useful field at $\nu > 100$ GHz and approaches the maximum practical mass at 100 mK for a space application. A significant improvement in sensitivity over Planck will be needed to map the polarization of cosmic microwave background anisotropy, yet clearly the HFI focal plane cannot be scaled up to 10^3 to 10^4 pixels. A post-Planck mission requires not

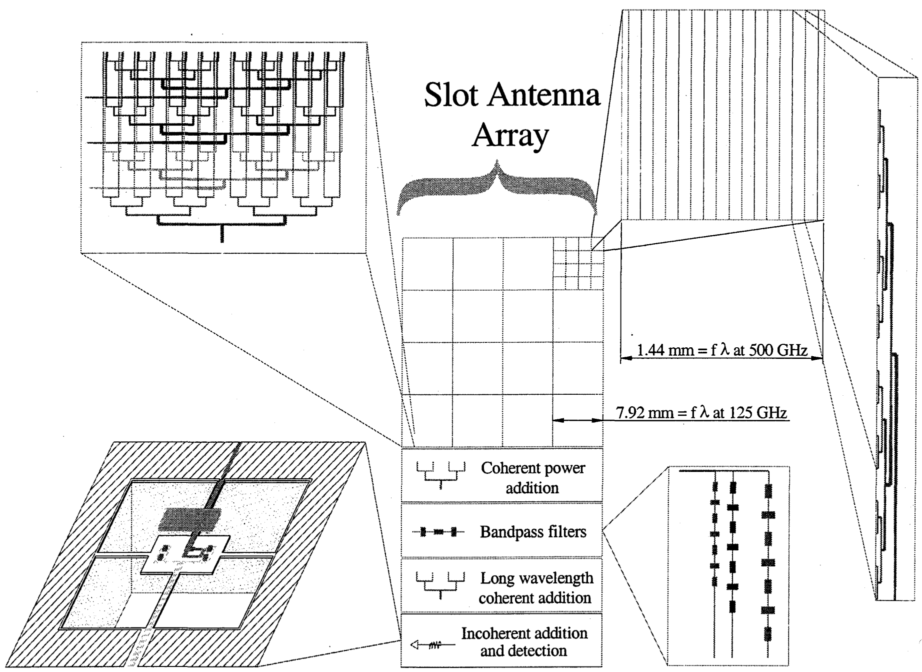

FIGURE 1. Focal plane architecture designed for polarimetry of the Cosmic Microwave Background (CMB) at the focus of an f/3.3 optical system. The focal plane contains 3 overlapping, close-packed arrays of synthesized, diffraction-limited pixels: a 4x4 array at 125 GHz, an 8x8 array at 250 GHz and a 16x16 array at 500 GHz. There are thus a total of 336 detectors coupled to an active area of 32x32 mm. A densely packed (100 μm slot spacing) array of slot antennas in a Nb ground plane deposited on a silicon wafer gives an antenna impedance of ~20 Ω. Microstrip taps cross the slot antennas at 100 micron intervals and are coherently summed, first along columns (inset, upper right), and then along rows (inset, upper left) to a single transmission line per diffraction-limited 500 GHz pixel. The microstrip is adiabatically tapered after each summation to maintain an impedance of 20 Ω. The microstrip lines pass through a bank of stripline filters, are coherently summed for the low frequency pixels, and terminate in a detector (inset, lower left).

only multiplexing, but a compact, low-mass focal plane that provides beam collimation without feedhorn optics.

We propose a new architecture for millimeter-wave focal plane arrays of bolometers coupled to antennae and filters via low-loss superconducting Nb microstrip. We are developing a concept for a polarization-sensitive bolometer array, shown in Fig. 1, that uses bolometers coupled to slot antenna array with superconducting Nb microstrip. Since the technical aspects of the multi-band, polarization-sensitive focal plane architecture are described in a parallel contribution [2], we describe the advantages of micro-strip coupling and future science applications.

MICROSTRIP-COUPLED BOLOMETERS

Microstrip-coupling provides several important advantages over coupling via conventional absorption onto a black surface. Antennas may be coupled to a bolometer by means of superconducting microstrip terminated in a resistor. Unlike a conventional absorber, which requires an active area at least as large as λ^2 in order to couple efficiently, the microstrip termination resistor may be as small as lithographic techniques permit. The termination resistor does not couple easily to stray radiation. Future space-borne applications in which a cooled aperture and/or narrow spectral bandwidth will reduce the background loads to fWs, stray radiation from 2 K alone (~1 pW/mm^2) makes use of bolometers with radiation absorbers intractable.

Antenna-coupled bolometers have a field-of-view defined by the antenna. In contrast, bolometers with radiation absorbers require single- or multi-mode feeds to define the field of view, or are subject to an urestricted view of stray light from 2π steradians. Feedhorns typically dominate the suspended mass and volume of the focal plane.

Antenna-coupled bolometers may take advantage of lithographed stripline filters. Stripline filters provide high transmission and excellent out-of-band rejection, and are a well-developed technology. They replace the much larger and more massive metal-mesh filters required by bolometers with radiation absorbers. The high frequency blocking requirements of mm-wave bolometers are quite severe. Antennas and microstrip do not efficiently propagate high frequency radiation.

Antenna-coupled bolometers have active areas that can be orders of magnitude smaller still than a micromesh bolometer. Our initial tests of stripline-coupled bolometers will use a normal metal resistor to terminate the stripline, and a separate trilayer TES with Nb leads for readout. This simple architecture, ideal for testing, can realize the sensitivity required for background-limited operation at 300 mK. However, significant improvement in detector sensitivity, possible due to the small active areas allowed by stripline coupling, could later be realized by any of a number of microstrip-coupled detectors (e.g. SQPC, HEB, kinetic inductance, e-phonon decoupled TES, etc).

The key to the successful implementation of microstrip-coupled bolometers is the ability to transport signals across macroscopic distances via superconducting microstrip transmisson line. Loss measurements on niobium superconducting films with an SiO dielectric layer is presented in a parallel contribution [3].

SCIENTIFIC APPLICATIONS

The decade of the spectrum from 100 GHz to 1 THz is rich in scientific content, yet remains one of the least explored. This region contains the bulk of the energy in the Cosmic Microwave Background (CMB), much of the Cosmic Infrared Background (CIB), believed to represent the integrated emission from ultra-luminous infrared galaxies at high redshifts, and virtually all of the observable emission from cool (T<15K) clouds in our own galaxy. It is in this range of wavelengths that significant advances in space astrophysics will best be realized: making definitive maps of the temperature and polarization anisotropy of the CMB, understanding the spectrum, spatial distribution and origins of the CIB, and unveiling the epoch in which the first stars and galaxies in the universe formed.

Inhomogeneities in the universe that are present at age 300,000 years are themselves the result of earlier processes. By studying degree angular scale CMB structure we learn about processes, inflation for example, that may have produced gravitational potential perturbations in the early universe. It has recently been determined [4] that the careful study of CMB structure, in particular degree angular scale *polarized* sky structure, can be used to detect not just potential perturbations but also gravitational waves. Unlike photons, these gravitational waves travel freely through the ionized early universe, so the study of CMB polarization may allow us to look much further back in time - and at much higher particle energies - than has been possible before. However, the sensitivity needed for these observations exceeds that attainable with the Planck satellite, and require a significant advance in focal plane format to 10^3 to 10^4 background-limited pixels. If a new instrument can be built with sufficient sensitivity to polarization, the resulting observations have the potential to allow the study of the physics that dominated the universe $\sim 10^{-33}$ seconds after the Big Bang.

CONCLUSIONS

Microstrip-coupled focal plane structures greatly reduce the size, mass, cooling requirements, risk, and cost of mm- and sub-mm focal planes for future space-borne astrophysics. We are analyzing and testing the Nb microstrip, RF filters, detector, and antenna array technologies required for a multi-color polarization-sensitive focal plane.

ACKNOWLEDGMENTS

The authors would like to acknowledge support from NASA grant NAG5-10317 and from the JPL DRDF.

REFERENCES

1. Turner, A. D. *et al.*, *Applied Optics*, in press.
2. Goldin, A. *et al.*. in these proceedings.
3. Vayonakis, A. *et al.* in these proceedings.
4. Caldwell, R. R. *et al.*, 1998, Phys. Rev. D 5902, 7101.